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POWDER TECHNOLOGY

Visual observations of individual particle behaviour in gas and liquid fluidized beds

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Abstract

The behaviour of the individual particles in dense gas and liquid fluidized beds and the behaviour of the jetsam particles in gas fluidized beds containing binary mixtures of different density group B powders has been observed. These visualizations have been made by means of an optical probe fitted with a conical glass cap making it possible to focus onto the particles. The individual particle mobility was observed to increase with decreasing cohesiveness and to be higher in liquid than in gas fluidized beds. The particles were seen to be in lasting contact, most of the time being largely immobile in a structure-like arrangement while being fluidized. This low particle mobility was apparent also in dry group B powders where interparticle cohesion is accepted to play a negligible role. Furthermore, the particle mobility was higher near the bottom of the bed and decreased towards the top of the bed, where the disturbances were less frequent and of larger scale. In the gas fluidized bed containing a binary mixture, heavier particles appear to be lying on a structure of touching glass ballotini. When provided with the opportunity through disturbances caused by rising bubbles they move through deficiencies and settle towards the bottom of the bed.

Keywords: Group B powders; Particle mobility; Particle behaviour; Interparticle cohesion; Binary mixtures

1. Introduction

Nowadays, gas fluidized beds are successfully applied to different physical and chemical processes, for example, solids mixing, solids drying, catalytic oil cracking and coal combustion. Liquid fluidization looks promising for crystallization, ion exchange, adsorption and other processes [1]. It is important for the modelling of processes occurring in fluidized beds to have knowledge about the nature of fluidized particles, how they move, how, if at all, they make contact and how segregation of atypical particles takes place. Some indirect knowledge about these topics has been gained in the past. By introducing interparticle forces in the fluidized bed, for example, by permanent magnetism of the particles [2], using a high gas humidity [3,4] or using non-volatile liquid layers on the particles [5], it was possible to change the fluidization behaviour of the particles. Therefore, it has been commonly accepted that the differences in fluidization behaviour of Geldart's powder groups are not only due to hydrodynamic effects but are also influenced by interparticle forces. Although measurements of the heat transfer in fixed and fluidized beds indicate that the particles are in contact while being fluidized [6,7], it has not been possible to determine conclusively the behaviour of individual particles in fluidized beds.

To investigate the particle motion, visual observations of the individual particles have been made at the riser wall of a cold model circulating fluidized bed [8,9]. The interaction of group B with group C powders in the dense phase of a fluidized bed has also been examined in this way [10]. By inserting probes into fluidized beds it is possible to measure locally the bubble properties and particle velocities [11]. Optic fibre probes have been used to determine particle velocities and concentrations in circulating fluidized beds [12–16]. Recently, it has become possible to visualize the individual particles within gas fluidized beds by means of special optical probes although the application has so far been limited to fast fluidized beds where a rapidly moving dispersed and cluster phase has been viewed [17–19]. In this study, the behaviour of the individual particles in bubbling gas and in liquid fluidized beds is observed with an optical probe. The individual particle behaviour in these beds and the behaviour of jetsam particles in gas fluidized beds of group B binary mixtures of different density is reported upon. Although these results are mainly qualitative, they are of great value in furthering the understanding of the nature of fluidized beds.

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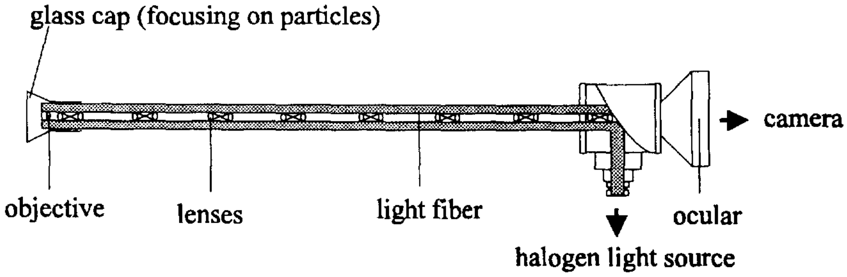

Fig. 1. Schematic diagram of the probe.

2. Experimental

The optical probe consists of a series of lenses within a hollow tube surrounded by optical fibres connected to an adjustable halogen light source (Fig. 1). An experimental type probe (7 mm diameter, 5 cm long) and a commercially available type (4 mm diameter, 17 cm long) both from Richard Wolf GmbH in Germany were used. A conical glass cap was used to prevent the particles from reaching the lens thus making it possible to focus on the particles. These devices had maximum diameters of 15 and 9 mm respectively. The images of the particles were collected by a charged coupled device (CCD) micro-camera (50 fields/s, 25 frames/s) connected to the ocular of the probe and using lenses with focal lengths of 27 and 75 mm respectively. An advanced video system and a monitor were used.

The probe was positioned horizontally in a fluidized bed column (6.6 cm i.d.) made of glass and fitted with a porous glass distributor. To ensure constant fluidization conditions, the relative humidity of the fluidizing gas was controlled by means of a humidification apparatus. The feed for this apparatus was dry air with 10% relative humidity coming from a compressor. The flow rate of dry air was set by means of an automatic controller and part of it was wetted in a water trickle-flow column filled with raschig rings. The dry and humid air streams were then mixed in a static mixer section, whereafter the relative humidity was measured and controlled automatically in a feed-back loop. Tap water was used for liquid fluidization. Observations were made in bubbling fluidized beds of 260–310 μm glass ballotini (d_{sv} = 281 μm, $\rho_p = 2500$ kg/m^3, $U_{mf} = 0.067$ m/s) and of 210–260 μm bronze particles ($d_{sv} = 235$ μm, $\rho_p = 8750$ kg/m^3, $U_{mf} = 0.19$ m/s) at gas velocities up to 0.25 m/s. Liquid fluidization of the 260–310 μm glass ballotini was performed at superficial velocities between 0.99×10^{-3} and 5.85×10^{-3} m/s ($U_{mf} = 0.90 \times 10^{-3}$ m/s calculated with the Ergun equation [20]).

3. Results and observations

3.1. *Freely bubbling group B powder*

The probe was inserted in the bed both vertically and horizontally. With vertical insertion, the region below the probe was clearly seen to be defluidized. Horizontal insertion of the probe into the bed appeared not to cause disturbances in the bed by the probe tip (although bubble formation was observed near the bed wall where the probe entered). Through the probe particles were seen to move away from and towards the probe. Also segregation of heavier particles was observed. This indicates that the particles in front of the glass cap are normally fluidized and their motion not hindered by the probe. It is therefore believed that the results obtained are representative for the particle behaviour in the bed.

Observations were made near the top of the bed (11.0 cm above the gas distributor) at different horizontal positions by simply pushing the probe further into the bed. The transition from the packed to the fluidized state when increasing the gas velocity was recognized by the passage of bubbles. A little rearrangement but no floating of particles was observed before this transition. In the bubbling fluidized state the individual particles were largely immobile being in lasting contact with each other and they were only moving when disturbed by rising fluidization bubbles. In Fig. 2, a sequence of pictures shows the passage of a bubble near the top of the fluidized bed. The bright circle covering part of the screen is the result of light reflecting in the glass cap. The bright circle within each glass particle is also due to a reflection effect. As the bubble approaches, the particles are pushed upwards and sideways while the individual particles maintain their relative position. In Fig. 2(a), the moving particles appear as unsharp streaks due to the exposure time of the camera. In Fig. 2(b), the empty internals of the bubble appear dark. Fig. 2(c), shows the particles just after the bubble passage where they are no longer moving upwards. At this point the voidage is still higher than in the bulk phase as a whole. Fig. 2(d), shows the particles settling to the normal bulk voidage. They then stay immobile until a new bubble approaches. The observed behaviour appeared consistent with particle movement as in a plastically deforming structure without much mobility of the individual particles. The momentum transfer in the bed appeared to be via particle–particle contacts which were lasting and not collisional. This is, unfortunately, less evident from the still pictures than from the moving film.

Near the wall, where no bubbles rose, the particles were moving downwards while largely maintaining their position within the arrangement of touching particles. Some deficiencies (holes of dimensions of the same order as the particles)

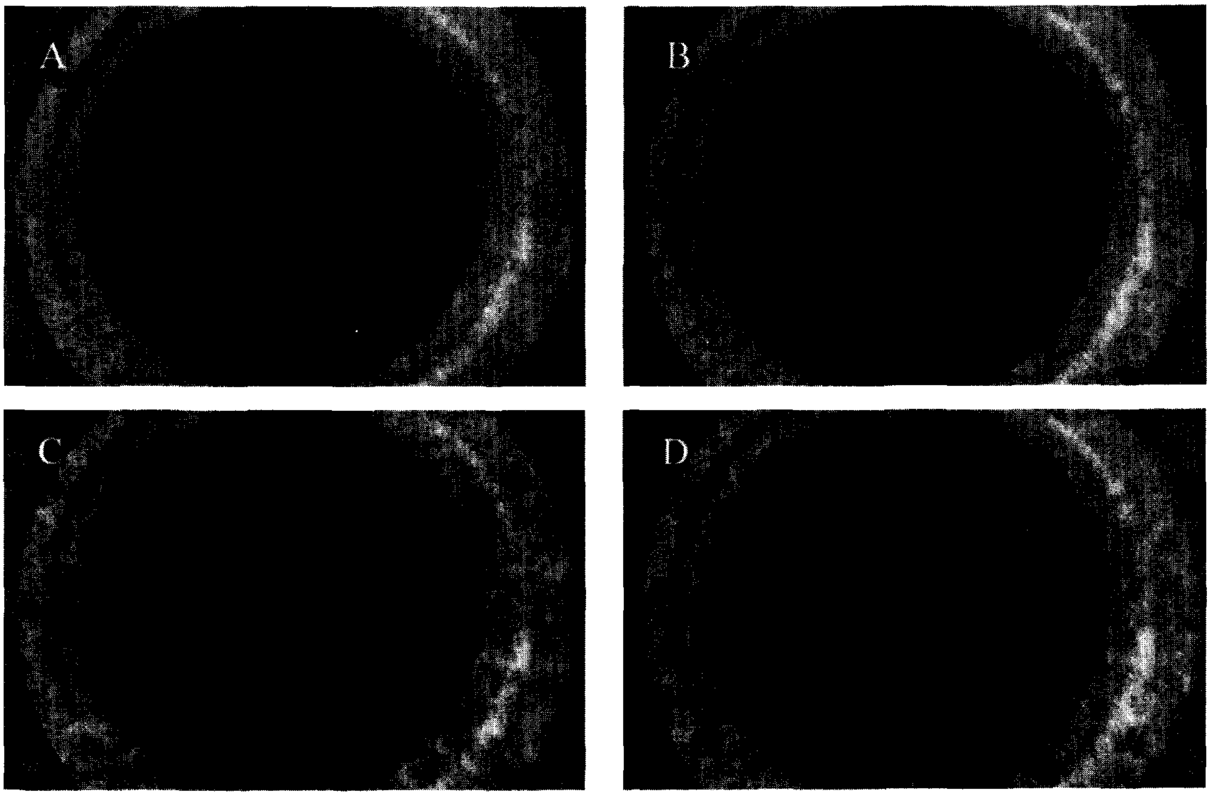

Fig. 2. Sequence of pictures showing the passage of a bubble. (Commercial probe: elapsed time between two pictures is 0.12 s, H_{bed} = 17 cm, H_{probe} = 11.0 cm, U_g = 0.08 m/s). (a), moving particles appear as unsharp streaks; (b), dark view of the empty internals of a bubble; (c), particles moving slowly upwards after a bubble; (d), particles returning to the dense phase voidage.

were always observed both near the top as near bottom of the bed. A deficiency has been indicated in Fig. 3(b).

In order to observe the particle behaviour close to a distributor plate, bronze powder was added to the bubbling fluidized bed of glass ballotini at gas velocities below its own minimum fluidization velocity. The bronze segregated to the bottom of the bed and acted as a gas distributor. Compared to higher up in the bed where the particles only move in response to the rising bubbles the particles moved continuously but on a smaller scale near the bronze powder distributor. As the voidage was clearly higher the individual particles could move and rearrange their relative positions. Although the mobility is higher, the particles still seem to be in lasting contact with each other.

3.2. Observations of segregating bronze particles

In a bubbling binary mixture of glass and bronze particles, the individual bronze particles appeared not to be supported in the gas stream but to be lying on a supporting structure of touching glass particles. The bronze particles segregated by falling through defects when provided with the opportunity as a consequence of a disturbance created by a rising gas bubble. A sequence of frames showing the segregation of a bronze particle close to a defluidized layer is given in Fig. 3. The movements of the indicated bronze particle and that of several glass particles (I–IV) were tracked. The results are given in Fig. 4. It can be seen in this figure that the motion of the jetsam particle is downwards, while the different bulk particles move arbitrarily around in the field of view.

Although the bubbles in the bed could not be seen clearly due to the very small field of view, it appeared that a jetsam-rich region exists behind a bubble. This agrees with observations of the mixing in two-dimensional fluidized beds [21] and it is now commonly accepted that jetsam rises in the wake of the bubbles. By adding a large amount of bronze at the top of the bed, it is even possible to defluidize part of the bed as a cluster of bronze particles forms which only segregates by increasing the gas velocity considerably.

3.3. The effect of the humidity on the fluidization of B powder

The effect of the humidity of the fluidizing gas on the 260–310 μm glass ballotini was also investigated. From the literature, it is known that increasing the gas relative humidity increases the interparticle forces [3,4]. When the relative humidity of the fluidization gas was increased from 45% in the freely bubbling experiments to about 65%, the particle mobility decreased and the number of deficiencies seemed to increase. When the humidity was increased above 65% the bubbling ceased and the particles became immobile. Sometimes it was observed that a few particles were blown away from a particular position after which a stable channel was

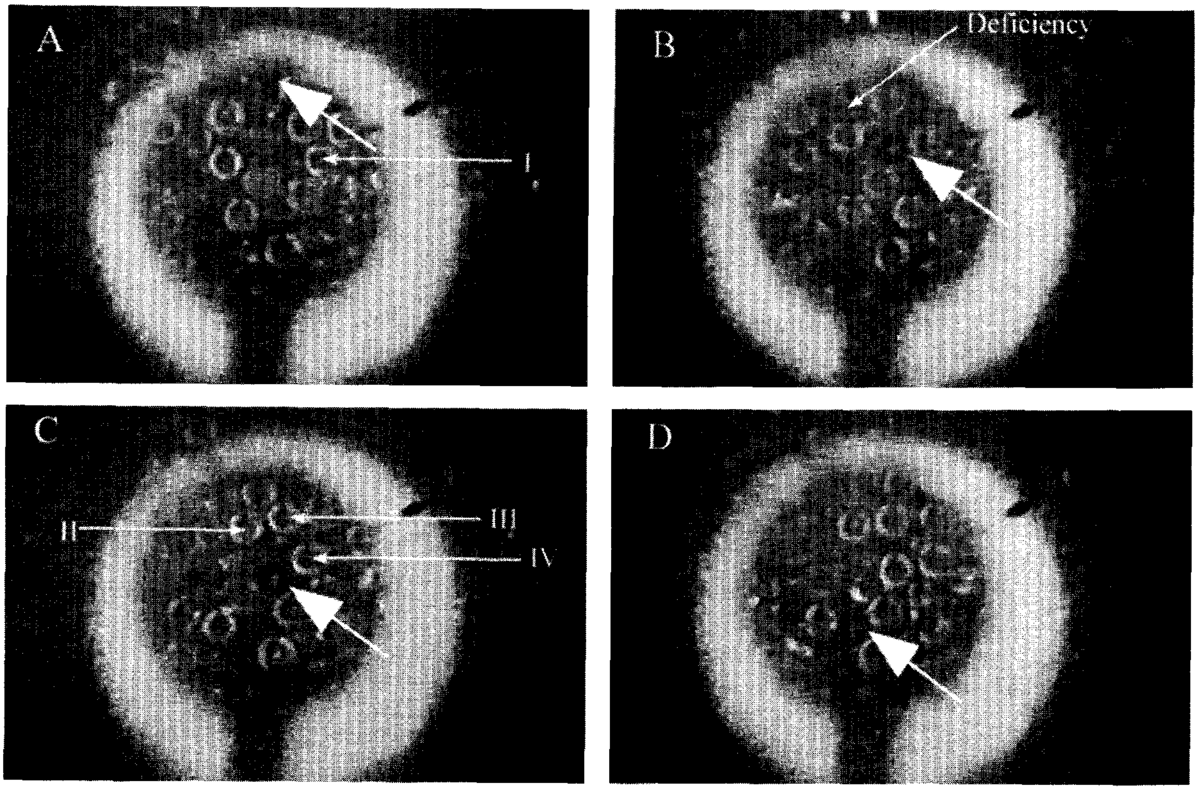

Fig. 3. Sequence of pictures showing the segregation of a bronze particle near the distributor. Experimental probe: elapsed time between two pictures is 0.12 s, $H_{bed}=20$ cm, $U_g=0.08$ m/s.

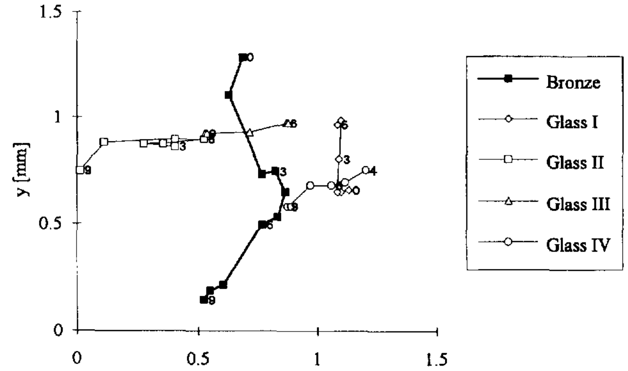

Fig. 4. Particle tracking showing the movement of a bronze and of various glass particles which are indicated in Fig. 3. The numbers in the figure correspond to the frame numbers (25 frames/s).

formed there. The powder thus defluidized at high relative humidities exhibiting a more cohesive behaviour which is sometimes referred to as exhibiting group C behaviour.

3.4. Liquid fluidization of glass ballotini

Observations made in liquid fluidized beds of glass ballotini showed an bubbleless expansion of the bed and an increase in voidage while increasing the liquid flow rate from 0.99×10^{-3} to 5.85×10^{-3} m/s. Contrary to gas fluidized beds, where particles are largely immobile in the absence of fluidization bubbles, intermittent streamlike flow of particles in changing directions was observed here, particularly at higher fluidization velocities. In the stream flow individual particles were observed to move relatively to other particles and to the direction of the stream. In spite of the higher mobility, the particles appeared to make lasting contacts which at the lower fluidization velocities resulted in the formation of intermittent largely immobile arrangements.

4. Discussion

The observation of constantly touching particles in the fluidized state agree with the assumptions of Gamson [6] and Mickley and Fairbanks [7] which they used to correlate heat and mass transfer measurements performed in fixed and fluidized beds. This arrangement of touching particles supported in the gas stream is present also when cohesion forces between the particles are negligible compared to other forces. Frictional resistance to sliding also appears to stabilize the formation of an arrangement of particles of low mobility. In this kind of arrangement the mobility of the individual particles depends on the frequency with which they are provided with the opportunity to leave their position which again depends on the disturbances caused by the fluidization bubbles, on the voidage and the frictional and (for cohesive powders) the cohesive forces between the particles.

In gas fluidized beds of group B powder with relatively insignificant interparticle cohesion forces, the observed limited mobility of the individual particles thus appears to be a consequence of the frictional resistance to sliding. Near to the top of the bed the voidage is low and bubbles are large which results in a low individual particle mobility. Near the gas distributor the voidage is higher and the smaller bubbles generate frequent small-scale disturbances which causes a higher particle mobility. Increasing the interparticle forces by humidification of the fluidizing gas creates cohesiveness of the powder which decreases the particle mobility and results in channel formation and a packing of completely immobile particles with dense and less dense regions. In liquid fluidized beds the particle mobility is quite high which is thought to be due to the lubrication effect of water decreasing the frictional resistance to sliding and also due to the more severe effects of flow perturbations in the fluidizing fluid in this kind of bed. Such a lubrication effect of water was also found in bulk density measurements [3].

5. Conclusions

From the observations in the group B gas fluidized beds and in liquid fluidized beds, it can be concluded that the particles are in lasting contact most of the time being largely immobile in a structure-like arrangement while being fluidized. This arrangement seems to be the result of interparticle friction forces and, in cohesive powders, it is stabilized by interparticle cohesion. As a result of these forces the individual particle mobility is lower in gas than in liquid fluidized beds. In a gas fluidized group B powder, the particle mobility decreases with increasing powder cohesiveness obtained by increasing the gas relative humidity. Furthermore, the particle mobility decreases towards the top of the bed, because the voidage is lower and disturbances are less frequent and of larger scale.

In the gas fluidized bed containing a binary mixture, heavier particles appear to be lying on a structure of touching glass ballotini. When provided with the opportunity, through disturbances caused by rising bubbles, they move through deficiencies and settle towards the bottom of the bed.

6. List of symbols

d_{sv}	average surface volume diameter (m)
H_{bed}	bed height (cm)
H_{probe}	height of probe insertion (cm)
U_g	superficial gas velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)

Greek letters

ρ_p	absolute particle density (kg/m^3)

Acknowledgements

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